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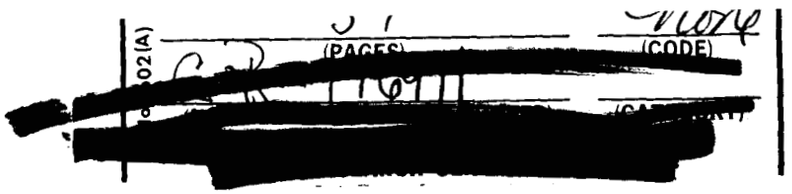

TR-64-211-4

LUNAR LANDING SITE CONSTRAINTS: THE ARGUMENTS FOR AND AGAINST ONE PRESELECTED SITE VERSUS SEVERAL SITES

January 31, 1964

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Washington, D. C.

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ABSTRACT

Trajectory and fuel constraints on the first Apollo mission limit the region of accessible landing areas to an equatorial band of ± 10° selenographic latitude. Additional constraints due to navigation, communication, and tracking requirements limit the extent of the band to approximately ± 45° longitude. Most of the area within the ± 10°, ± 45° region can be reached every day of the month.

However, constraints imposed by the lunar environment introduce a longitude effect which makes a particular site in the outlined region more favorable to the surface phase of the mission during some days of the month than others. The two most important factors of surface lighting conditions, necessary for astronaut participation in the LEM landing, and the surface thermal conditions could limit the availability of a single site to only 2.3 days per month. Allowing only a single launch window per day from the earth, this would lead to a rather inflexible program.

In an effort to increase program flexibility, one must at least consider the possibility of multiple sites. Four sites in the ± 45° interval could increase the number of consecutive launch days per month from 2.3 to 9. The advantage of this flexibility, however, must be weighed against the cost of surveying additional sites. The decision

as to the number of appropriate preselected sites must necessarily wait on the unmanned program results, as they may considerably relax the constraint picture and make the single surveyed site quite adequate.

Purpose and Scope

The purpose of this paper is to: (a) describe the various constraints which limit site availability on the lunar surface, (b) discuss to what extent these constraints limit launch opportunities to a single site or multiple sites, and (c) indicate what tradeoffs are possible in the way of constraint countermeasures. The general area of site location is outlined, but in view of the meager data on small scale lunar surface characteristics, no particular sites are suggested at this time.

LUNAR LANDING SITE CONSTRAINTS: THE ARGUMENTS FOR AND AGAINST ONE PRESELECTED SITE VERSUS SEVERAL SITES

INTRODUCTION

The net effect of Apollo systems requirements and lunar environmental factors on the availability of possible landing areas on the lunar surface can be severe. In an effort to make the entire program as flexible as possible, with due regard to the cost of increased flexibility, a judicious choice of a single site or array of sites can be made, subject to the several imposed constraints. In general the possible areas will be found to lie within a lunar equatorial belt, the actual position inside of this belt being a function of sun-earth-moon geometry. A knowledge of the availability of a given single site will then allow us to analyze the problem of whether a single site is adequate for the first mission, or whether the flexibility of multiple sites, implying increased launch opportunities, is justifiable in terms of the additional site certification effort.

Perhaps it would be desirable at this initial stage to indicate just what is likely to constitute a certified site, since the certification process itself may impose constraints which must be considered. One program may be complementary Surveyor-Photographic Orbiter coverage of an area whose radius is twice the LEM c.e.p. In fact, this program would include Surveyor data on LEM hazards inside a 500 meter radius circle,

and the lower resolution (by a factor of 4) Orbiter coverage of up to 900 square kilometers of area containing the Surveyor position. The Orbiter should place no restrictions on site locations, but Surveyors are essentially limited to landing on the western half of the previously mentioned equatorial belt.

In the event that the unmanned program indicates an unusually hazardous surface over a large percentage of the moon, an LRM may be required for site certification. In this case both the east and west halves of the equatorial belt would be available for the certification program, and thus possibly for Apollo landings. An LRM program is so tentative at this time, however, that the Surveyor-Photographic Orbiter mode will be assumed the more likely.

LANDING SITE CONSTRAINTS

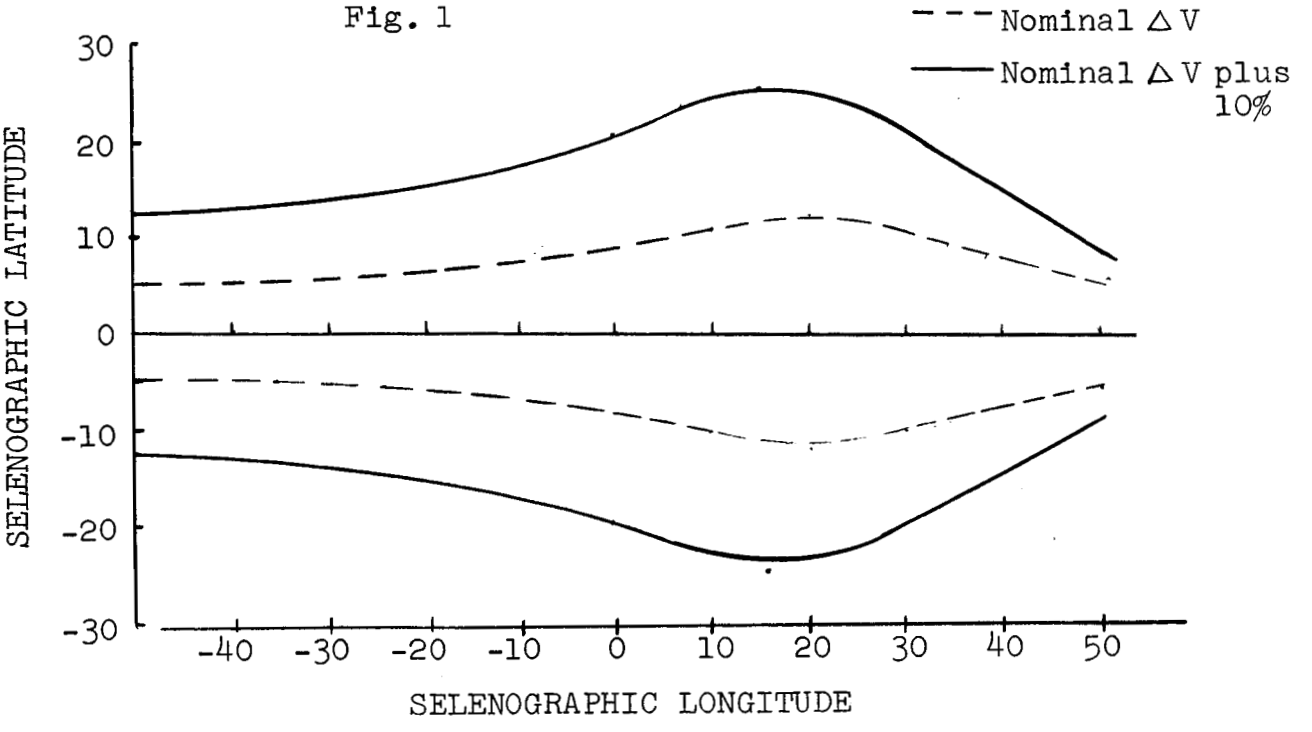
The various constraints which limit the availability of potential lunar landing areas may be subdivided on several different bases. One which seems appropriate here would be to consider first those constraints which eliminate given areas all the time, and then, for the accessible region remaining, consider how the rest of the constraints change the accessible sub-region as a function of time. With this approach in mind, we shall concentrate first on the availability of a single preselected site and then, if this appears too restrictive, consider the increase in launch opportunities per month derived from multiple sites.

(a) Fuel ($_{\Delta}V$) and Trajectory

The early Apollo mission requirement that the translunar trajectory be of the "free return" type, coupled with the

limited SM fuel budget, will limit the circular orbit of the LEM-CSM to low angles of inclination relative to the lunar equator. Since the LEM descent to the surface will be in the CSM plane, potential landing sites are limited to low selenographic latitudes. In general this constraint eliminates all the area outside of the equatorial band bounded by 10° N and 10° S latitude. A quantitative examination of this problem has been made at Bellcomm[1] (see Figure 1).

Fig. 1



The area enclosed by the dotted lines represents that which can be reached with the nominal ΔV budget 100% of the month in 1969 for a mission based on a 70-hour translunar flight time and 65-hour transearth flight time. The outer pair of lines enclose the area accessible given the nominal ΔV budget plus 10%. On any individual day within the month the area is increased and will experience a small amount of rotation and translation.

We now ask the question of whether there are any general constraints in longitude. Here there are several effects to consider, the result of which is a limitation for sites to lie between roughly 45° E and 45° W. Sections (b) through (d) will define these in some detail.

(b) Guidance and Navigation

Once the Apollo vehicle achieves a circular orbit around the moon, the primary mode of navigational updating will be the measurement of angles between some reference frame (star or inertial platform) and previously chosen landmarks on the lunar surface. The combined effect of the position of these landmarks and the LEM descent trajectory places some limitation on the prospective site location. MIT has specified use of five landmarks, located to 1500 foot accuracy (1 sigma), and lying approximatley on the equator at 30° intervals. Until such time as we have accurate photographs of the back side of the moon, these landmarks must necessarily lie on the face. One mode of operation suggested by MIT would be to fly one complete circular orbit, passing over each landmark once, and then initiate LEM separation shortly after the first landmark was passed over a second time. This would allow a navigational updating after the pass around the back of the moon, where no sightings are made, and just before the critical separation maneuver. If no landmark is in view just prior to separation, an angle will be measured to the lunar horizon, but this results in a larger position and velocity error.

For landmarks located at 0°, ±30°, and ±60°, and assuming that the LEM traces out approximately 100° of central angle between deboost and landing, the landing position would be west of 40° west longitude. This is a rather severe limitation and, for a number of reasons, may not be the likely case.

First of all, the same uncertainty in locating the landmarks also applies to locating the landing site. Current ACIC estimates of the probable error in locating control points on the lunar surface give 1740 meters at selenographic coordinates 0°, 0°, increasing on the equator as the secant of the longitude. Efforts are under way to decrease these errors by a factor of two in the next couple years. In this case there will be some tradeoff between choosing the site close to 0° longitude for more accurate site location, and choosing it further west for increased confidence in the position of the final landmark to be used in updating the orbit.

And secondly, the status of control point uncertainty on the moon may be altered significantly by the unmanned program. The use of wide angle camera photographs in conjunction with data on the camera (Lunar Orbiter) position and attitude relative to the earth and moon* may decrease the uncertainty in the control points mapped most accurately from earth, and in addition extend the range of control points with equal probable error around to the back of the moon. In this latter case

* Leon Kosofsky, OSS Orbiter Briefing, January 15, 1964

landmark accuracy would impose no constraints on the site position.

(c) Surveyor

If a successful Surveyor mission is required for site certification, then Apollo landing areas must fall within the general region accessible to a Surveyor probe. According to current design plans, Surveyors will not land east of 5° east longitude; this would limit potential landing sites to the western half of the equatorial belt.

(d) Communication and Tracking

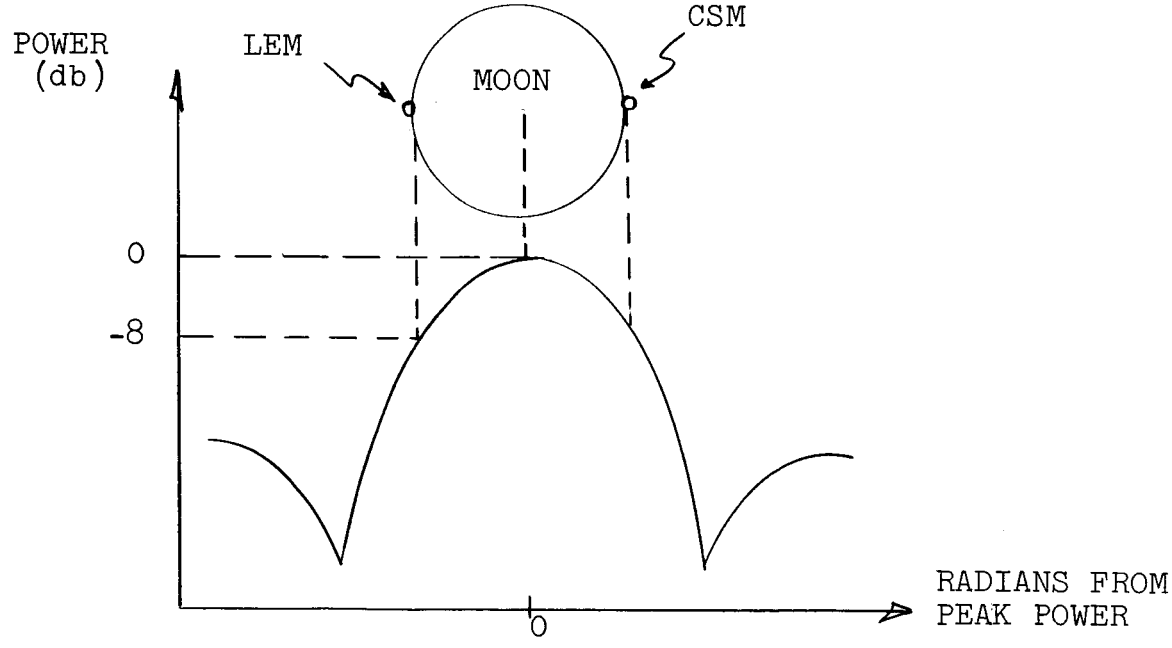
There is a suggested requirement that the LEM deboost into elliptic orbit within sight of the earth. All periods of thrust are critical, and it is certainly desirable to maintain a communication link with the earth at such times. Due to the 100° central angle between the deboost and touchdown positions, the landing site would have to lie on the west side of the moon.

Similarly there is a suggestion that communications and a tracking back-up mode from earth be in operation during LEM ascent from the lunar surface. About 10 minutes of tracking data would be required before the LEM disappears behind the moon. This constraint would require that the landing area be east of about 60° west.

Another communication constraint is that of simultaneous communication between an earth-based DSIF station and both

the CM and LEM after LEM separation. The problem stems from the fact that the two modules, conceivably as much as a lunar diameter apart, cannot both be at the peak power point of a single, narrow beam DSIF antenna pattern at the same time. Unless the DSIF network is improved, a single station must be able to cover both vehicles. As an example, consider the case (Fig. 2) of the landed LEM on the west limb and the CSM just coming into view around the east limb. The logical tradeoff is to point the DSIF antenna at an intermediate position which is weighted by the transmitting properties of LEM and CSM systems.

Fig. 2



DSIF ANTENNA PATTERN

The question arises as to whether the signal-to-noise ratio in each of the two systems is adequately maintained during the tradeoff, since neither system will operate at the peak of the DSIF pattern. The best case, or minimum signal loss, occurs when the LEM lands at 0° longitude, and then the maximum module separation is a lunar radius.

Examination of the proposed operating characteristics of the two module subsystems indicates that this constraint can essentially be relaxed, although the most taxing case of TV transmission from both modules simultaneously at a separation of one lunar diameter is marginal.

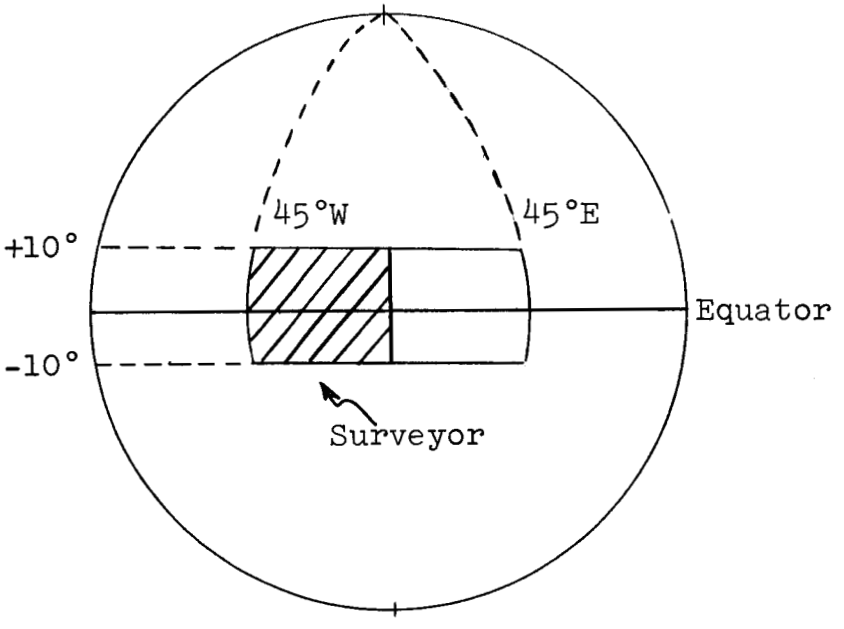
SUMMARY OF TIME INVARIANT CONSTRAINTS

Before discussing the time varying constraints, it would be instructive to summarize in a simple diagram just what region on the moon's surface remains after the application of constraints (a) - (d). The boundary parallel to the lunar equator is a fairly hard constraint and will be taken as ±10°. It is evident, however, that the boundaries in longitude will depend on how we weight the various requirements. For the present we shall adopt the lines of ±45° longitude without the Surveyor, and 0° - 45°W when the Surveyor becomes necessary. The ±45° is a compromise between keeping the landing site near 0°, 0° where it can be located more accurately for guidance and navigation purposes, and maintaining enough operating room so that when the remaining constraints are considered

there will be some reasonable number of launch windows per month during which a site may be reached. This latter point is in anticipation of using multiple sites to counteract the time varying constraints, and will be discussed in the next section.

Figure 3 then will act as the starting point for the remaining discussion.

Fig. 3



AREA OF POSSIBLE LUNAR LANDING SITES
FOR APOLLO

TIME VARYING CONSTRAINTS

The time varying constraints are in general those lunar environmental factors which, for a given landing site, make the assurance of that part of the mission involving LEM and astronaut contact with the surface a function of time. The factors to be considered are surface lighting conditions, surface temperature, and the hazards due to meteoroids and solar flare radiation.

Each factor acts independently, and it would be a rare case indeed if their favorable periods were all coincident. In general, we can expect to be forced to assign some compromise weighting to each constraint in order not to eliminate completely all launch windows to the selected site. If the limited number of launch windows in a year to a single site is such as to cause large delays in the program, then additional sites must be selected with non-coincident favorable launch periods.

In addition to the lunar environmental constraints there exists a tentative requirement for daylight earth launch which, if considered, would limit launch opportunities to certain months of the year. Of the two launch windows available each day, the one which makes the smaller dihedral angle with the earth-moon plane will most likely be used for reasons of fuel economy. The period of the year when this so-called in-plane launch also occurs during daylight at the Cape occurs in the spring and summer months for the 70°-108° launch azimuth range. The argument for daylight launch rests mainly on the desire for optimum search conditions in the event of mission abort.

This possible constraint is distinct from the other four time varying constraints in that, where they depend on the moon's rotation about its own axis, the earth lighting conditions do not. The effect is to make the lunar environmental conditions a function of time for a given position on the moon, or a function of position on the moon at a given time; the launch lighting constraint

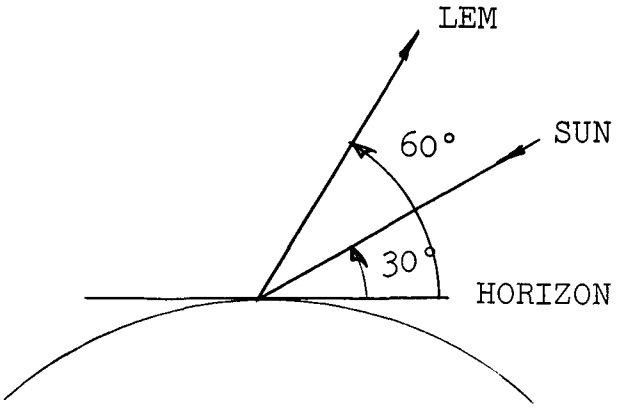
eliminates all potential sites at the same time, and therefore is not germane to the question of the desirability of one site versus multiple sites.

(a) Lunar Surface Lighting Conditions

Optimum lighting conditions are required at the landing area so that the astronaut guiding the LEM can distinguish between a hazardous and acceptable touchdown position. This is a logical requirement since even a certified site is not likely to be 100% landable. The ability of the astronaut to observe the surface geometry will depend upon the amount of information he can derive from both shadows and surface illumination contrast as a function of slope.

The contrast information may be the only key to the average slope, whereas shadows may be used to locate protuberances. A description of the expected contrast as a function of slope is derived from the lunar photometric function. This empirical function describes the scattered light intensity as a function of the geometry of the source and receiving positions (sun and astronaut) and the scattering surface (moon) orientation. The important conclusion derived from the photometric function is that the maximum change in scattered light intensity (contrast) per unit change in slope angle occurs when the observer is 60° above the horizon and the sun is 30° above the horizon and behind the observer (Figure 4).

Fig. 4



PHOTOMETRIC CONSTRAINT - OPTIMUM VIEWING CONDITIONS

Strictly speaking this refers only to the component of the slope in the plane defined by the incident and reflected ray paths.

The critical angle in Figure 4 is the angle of the sun above the horizon, since for a given site this angle depends upon the time of the lunar day (sidereal month). Although the 30° sun angle offers the best viewing conditions, some range of sun angles around 30° will prove adequate. This range is limited at the low end to 10° to avoid the excessive shadowing and decreased illumination near the terminator. The upper limit lies between 40° and 60°, with viewing conditions generally degrading as the sun angle increases.

The angle of the sun above the horizon at a given point equals the central angle of that point from the terminator.

Therefore the area of proper viewing conditions is 10°-40° (or 10°-60°) from either terminator on the sunlit side of the moon. For one of these areas the nominal LEM trajectory would be into the sun. However, a buttonhook trajectory has been shown* to be within the fuel budget; this would satisfy the photometric constraint of keeping the sun behind the LEM during the critical surface viewing time, thereby making both 30° (or 50°) sectors available for possible landing sites.

What is of interest here is just what percentage of the month a single site anywhere within the equatorial belt of Figure 3 satisfies the photometric constraint.

The moon's rotation moves a fixed site through the acceptable photometric area at the rate of 13°/day. This makes a single landing site available only 2.3 days per month, taking the upper sun angle limit at 40° and discounting the possibility of a buttonhook LEM trajectory.

Allowing the buttonhook operation gives two 2.3 day periods each month separated by about 8 days at the closer proximity. Assuming the single in-plane, daily launch window from earth, this means there are either one or two separate periods per month, each with 2-3 consecutive daily launch windows to a single site.

Operations planning people would like to have a 3-4 consecutive day launch period. Accepting the 10°-60° photometric

* R A Kaenel, Bellcomm

constraint increases the consecutive day period from 2.3 to 3.8 days. An alternative to relaxing the photometric constraint would be to have two sites separated by 30° of longitude in the equatorial band. Assuming a 10°-40° sun angle, this would give two 4.6 consecutive day periods separated by about 5 days at the closer proximity. This alternative will be considered in more detail later.

(b) Lunar Surface Temperatures

A ground rule for the first Apollo mission specifies a 24-hour LEM-astronaut stay time on the lunar surface. Adequate thermal protection can be provided for the astronauts by space suits designed for either lunar day or lunar night, but the task of designing for both on the first mission may be too demanding. Since the photometric function constrains the landing site to the sunlit side of the moon, the only problem so far as temperature is concerned is to keep the site from rotating through a terminator during the stay time.

Figure 5 is a theoretical temperature vs. solar phase angle curve suggested by Sinton (2). This indicates the rapid change of temperature with time near the terminator.

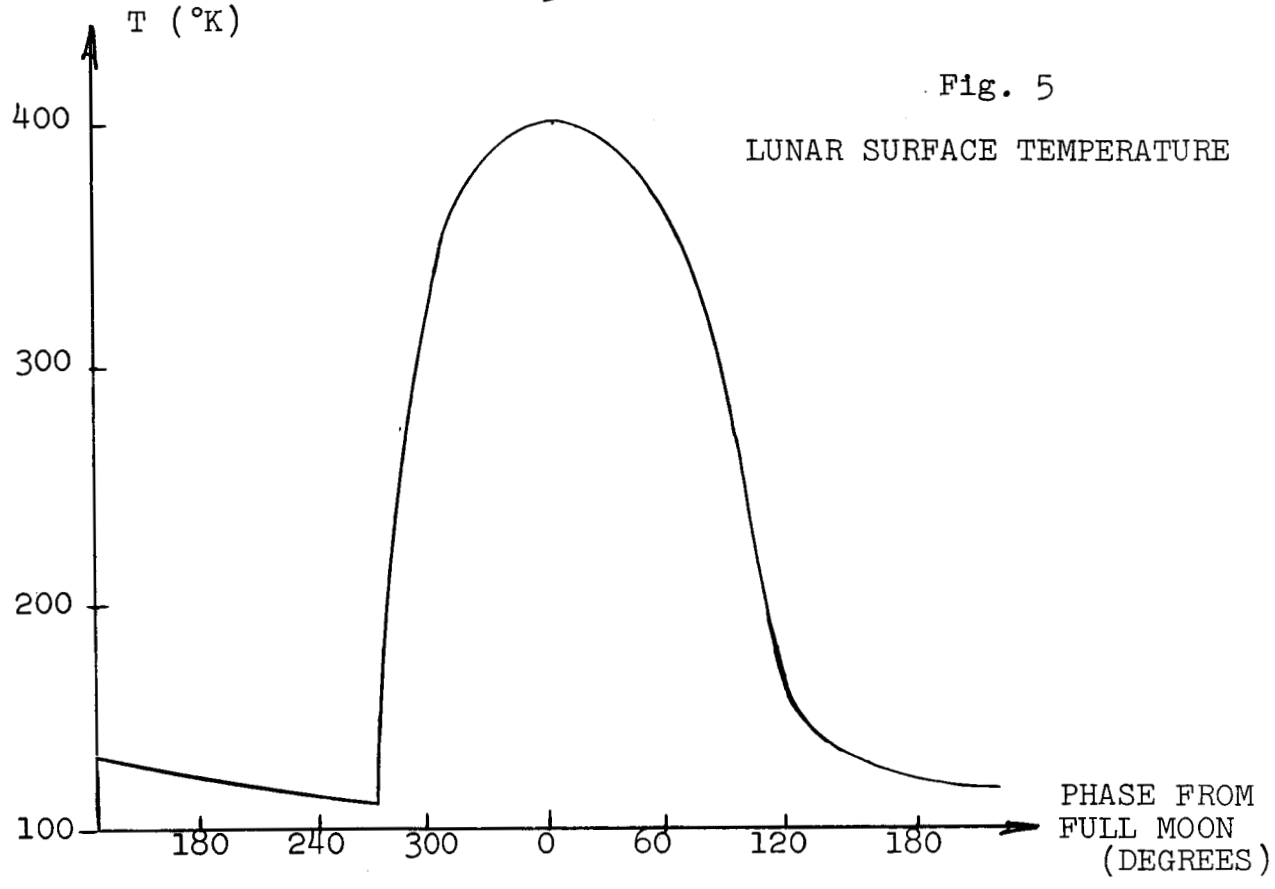


Fig. 5

LUNAR SURFACE TEMPERATURE

In particular we consider the extremely rapid fall in temperature at the evening terminator. In the case of a LEM landing 10° from this terminator, a 24 hour stay time would take the astronaut 3° beyond the terminator before LEM ascent. For the case of the morning terminator, surface stay time merely moves the mission towards lunar noon, which is quite acceptable.

In summary, then, the temperature constraint coincides quite well with the photometric constraint, with the slight modification that their net effect may change the lower bound on the sun's angle above the horizon at the evening terminator from 10° to 15°.

(c) Meteoroid Hazard

The meteoroid influx to the unprotected lunar surface may constitute a hazard to the astronaut. However, the large uncertainty in the meteoroid flux vs. mass curve makes this a difficult problem to evaluate. If the flux turns out to be at the high end of the present estimates, the hazard exists; if not, there may be no problem.

In view of the uncertainties this is perhaps a minor constraint. However, until such time as it can actually be dismissed (pertinent data is expected from the SA-9 meteoroid experiment), some consideration must be allotted.

Two periods may be associated with the meteoroid influx, one on a yearly basis and the second, due to the moon's rotation, on a monthly basis. Sporadic meteoroids, which comprise most of the integrated count, have a flux which on a yearly basis is at minimum during February and a maximum during July, the difference being a factor of approximately 4. On a monthly basis the sporadic meteoroid data indicate that a general area exists on the surface where the astronaut would be shielded by the moon itself from a large percentage of the influx. Figure 6, after Hawkins[3], is a polar plot centered at the earth (or moon) where the length of the radius vector (R) is a measure of the relative meteoroid flux coming from the θ direction.

Fig. 6

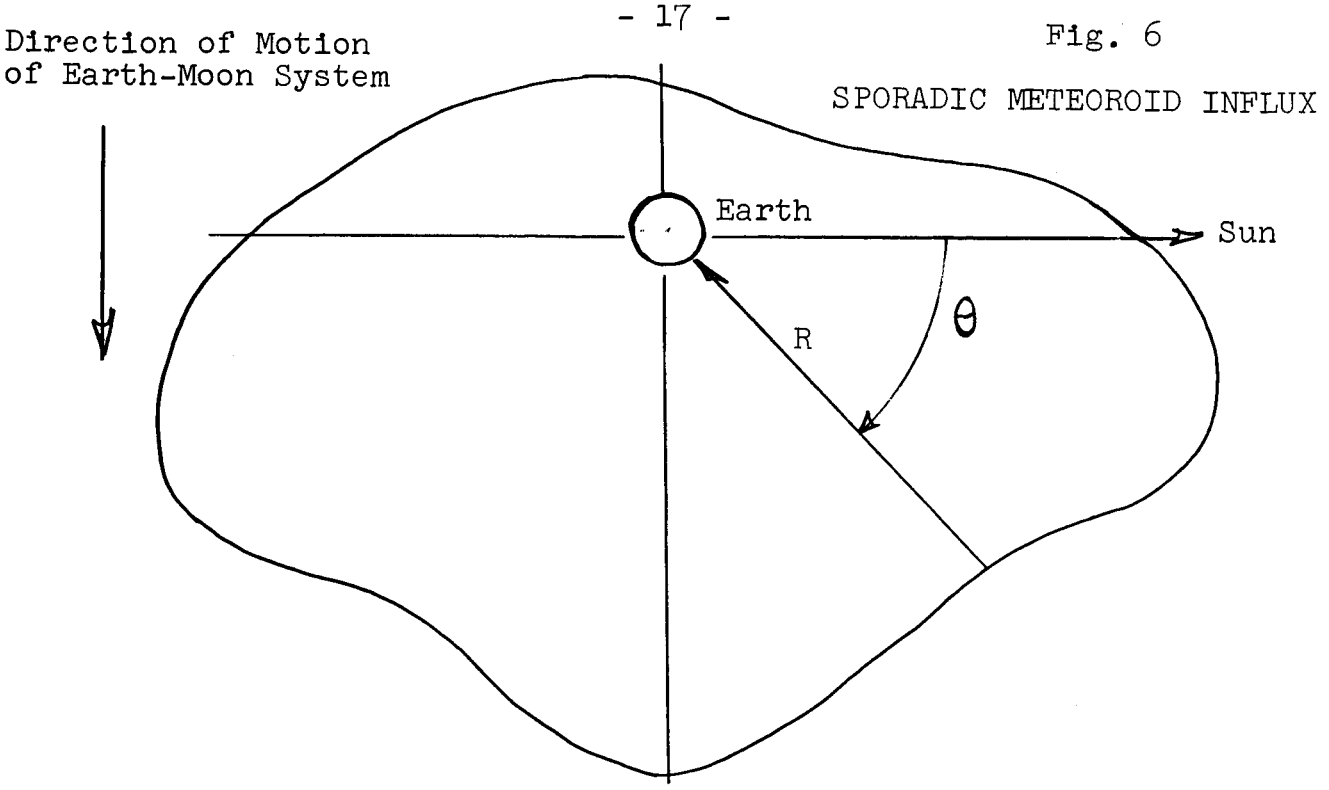


Figure 6 applies specifically to the sporadic meteoroids. Assuming care is taken to avoid mission coincidence with the stream meteors, Figure 6 can be used as the constraint determinant. It is apparent that most of the meteoroids strike the surface of the earth or moon because they have been overtaken by the fast moving earth-moon system on its way around the sun. Most of these meteoroids are themselves traveling in the same direction as the earth-moon system, but at a slower rate. With this in mind, then, there appears to be an advantage to choosing the landing site on the trailing side of the moon. Due to the moon's rotation, this makes the availability of a given site time varying.

In summary, then, we can consider the meteoroid hazard a minor constraint relative to the photometric and thermal

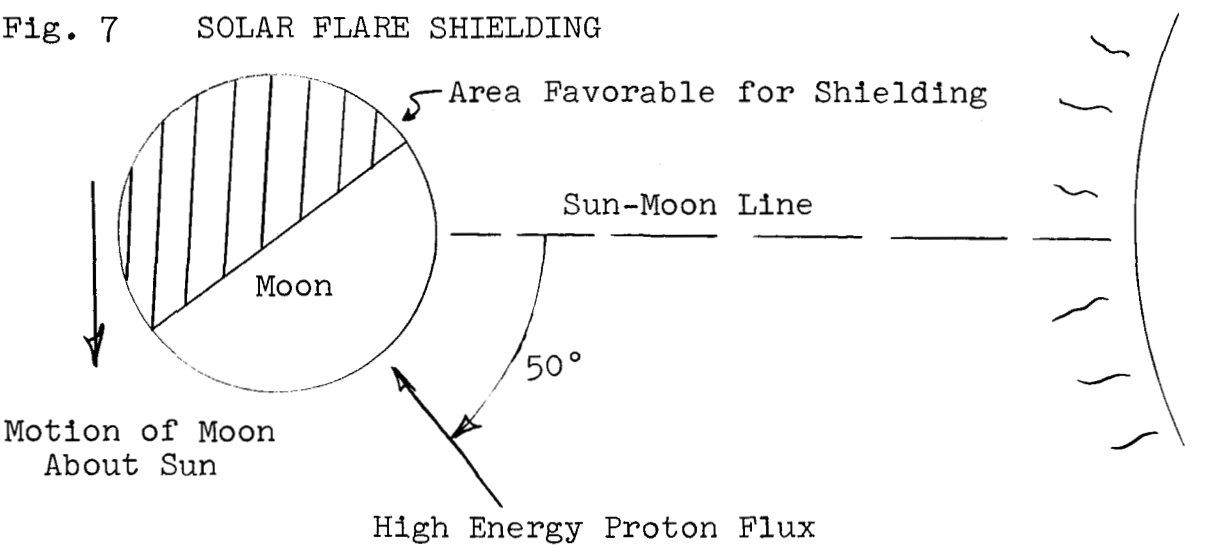
constraints, bearing in mind, however, that an order of magnitude difference in flux exists between the better half of the best month and the worse half of the worst month of the year.

(d) Radiation Hazard

The risk of having an astronaut on the lunar surface during a large solar flare should be avoided if possible. However, the lack of understanding of the flare mechanism and the inability to predict even the largest events makes any warning virtually impossible at this time. The only strategy seems to be to abort the surface mission when the radiation count gets above a prescribed level.

One observational fact concerning flares may place a low order constraint on the landing site location - on the average 10% of the integrated proton flux is directional; the remaining 90% is isotropic. The directional component, concentrated at the high end of the spectrum, appears to come from a direction 50° off the moon-sun line (see Figure 7).

Fig. 7 SOLAR FLARE SHIELDING



Therefore locating the landing site on the hemisphere opposite the directional component would expose the astronaut to 45% of the incident flux, as opposed to 55% on the other side. This seems rather insignificant in view of all of the other uncertainties.

It has been suggested that the months of June and December, when the earth crosses the assumed solar magnetic equator, have a minimum in proton flux at the earth (or moon), but the paucity of samples leaves the statistics too uncertain at this time to suggest a launch constraint which confines the acceptable period to these two months.

SUMMARY OF ALL CONSTRAINTS

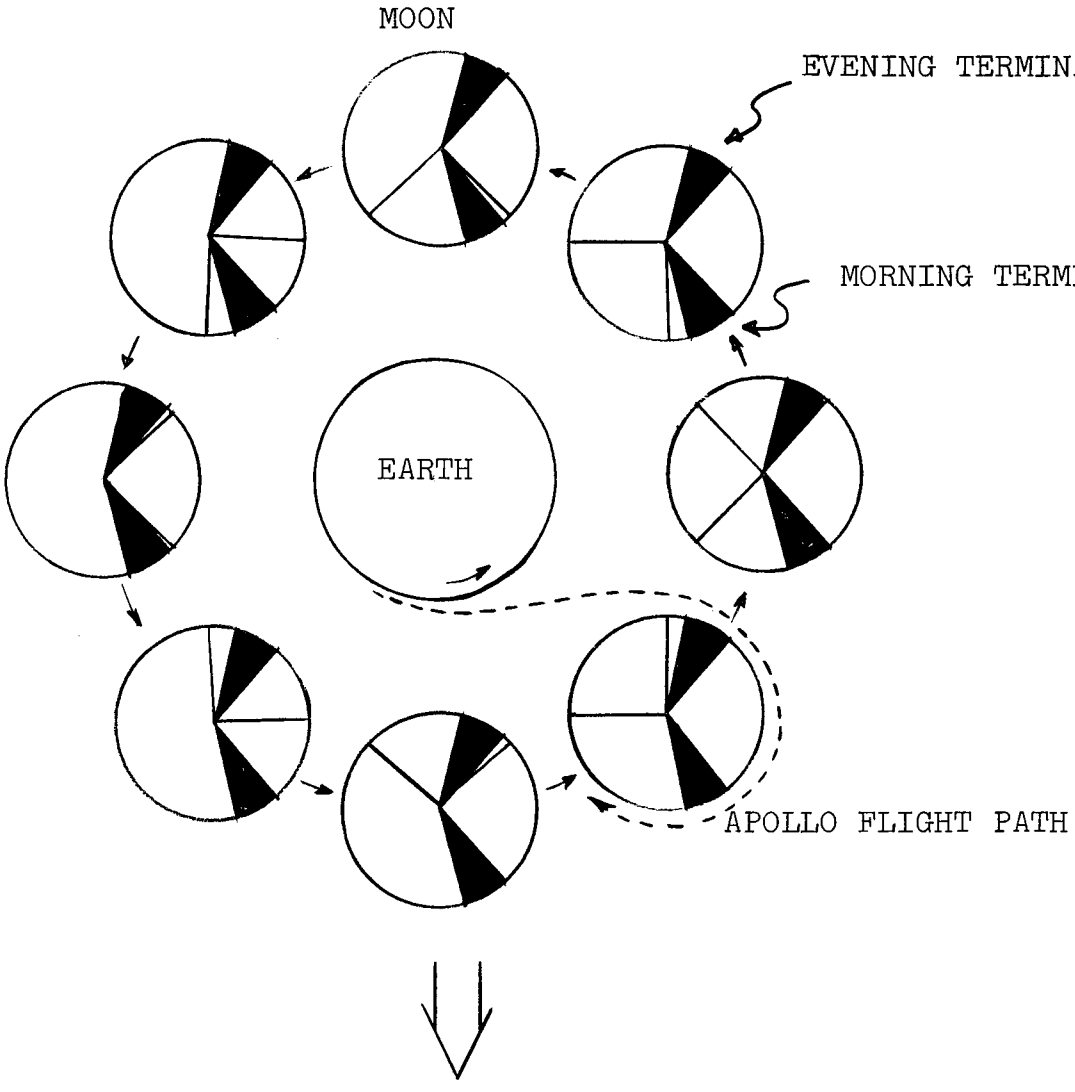
The major constraints are considered to be those which were considered as time invariant, as summarized in Figure 3, plus the photometric and surface temperature factors. These are summarized in Figure 8. The relatively minor environmental constraints due to the meteoroid and radiation hazards will be illustrated in Figure 9 for supplemental consideration.

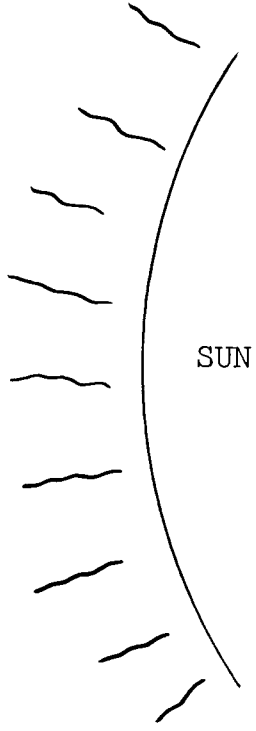
Figure 8 describes the sun-earth-moon geometry as the moon executes its monthly rotation about the earth. As this figure is two dimensional, it only approximates the constraint effect on lunar longitude; the ±10° selenographic latitude limitation of Figure 3 is understood.

The important features of Figure 8 are as follows: the 90° wedge opening towards the earth is the ±45° longitudinal constraint of Figure 3; and the two 30° shaded wedges represent the 10° - 40° example of photometric constraint.

The temperature constraint is automatically considered, assuming we retain the option to change the dimensions of the wedge near the evening terminator from 10° - 40° to perhaps 15° - 40°. It is also clear from this figure that the nominal LEM direction will be into the sun for landing sites near the evening terminator. Without a buttonhook trajectory to change

Fig. 8 MAJOR CONSTRAINT SUMMARY



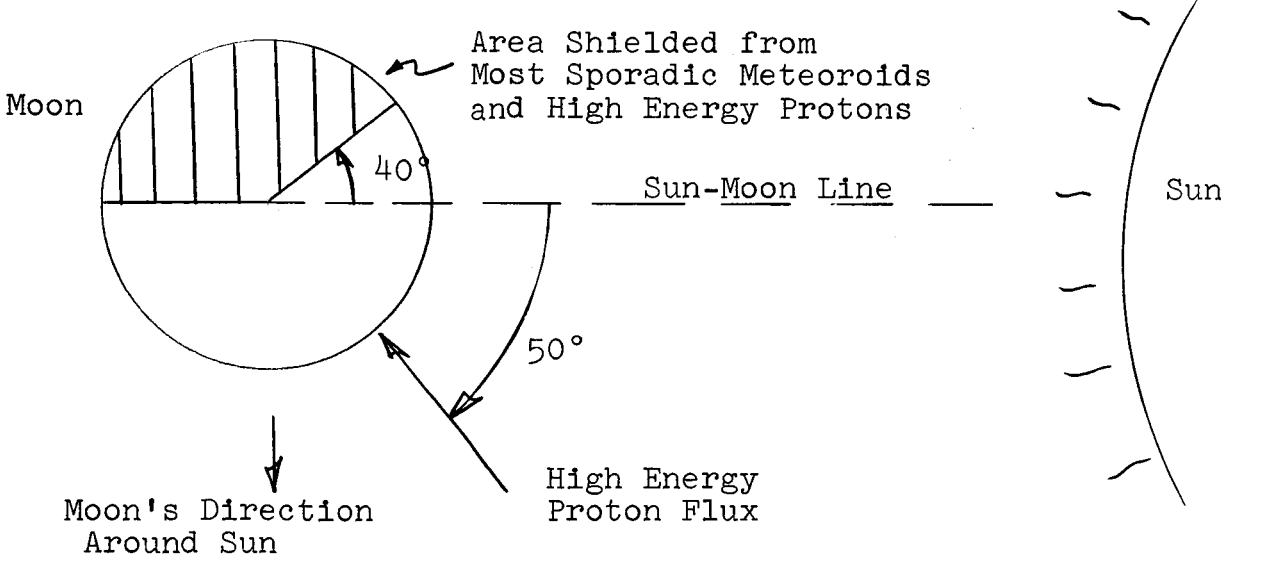


the direction of the LEM approach to the surface, this wedge would have to be eliminated on the basis of the photometric constraint.

Favorable lighting and thermal conditions exist during those periods of the month when a shaded wedge falls within the 90° wedge. The problem is then to have the landing site under both wedges at the same time. In addition we must consider the possibility of a daylight launch constraint. This, combined with the in-plane dihedral launch angle requirement, could limit the months during which Figure 8 is applicable to the spring and summer with essentially no launches allowed to any site during the fall and winter months.

For purposes of completeness the minor hazard constraints are indicated in Figure 9.

Fig. 9 METEOROID AND RADIATION SHIELDING ON THE LUNAR SURFACE



The moon in Figure 9 would be superimposed without rotation on each of the 8 moon's of Figure 8. Notice that the net effect, if these hazard constraints were followed, would be to eliminate the favorable photometric - temperature wedge near the morning terminator.

APOLLO REQUIREMENTS FOR MULTIPLE SITES

The net effect of the major constraints is to limit the availability of a single preselected site to possibly just a few days per month. Increased program flexibility may be achieved in several ways. The first, and one of the easiest, is to relax the constraints. The direct implication of this is a decreasing confidence in overall mission success. An alternative approach is to certify more than one site and space the sites at proper intervals to insure maximum accessibility. For example, allowing only the single 10° - 40° photometric wedge near the morning terminator, the placement of 4 sites at 45° W, 15° W, 15° E, and 45° E would give continuous coverage for $\frac{90 + 30}{360} = 33\%$ of the month. The strategy followed in the case of multiple sites would be to compensate for a launch date slippage by shifting to a new site.

The following table illustrates the effect of the several constraints on the site availability picture.

PERCENTAGE OF MONTH AVAILABLE

Constraints	Single Site	Multiple Sites 0 - 45° W	Multiple Sites 45° E - 45° W
10-40° Wedge Morning Terminator only	$\frac{30}{360}$ = 8 %	$\frac{45 + 30}{360}$ = 21% (3)	$\frac{90 + 30}{360}$ = 33% (4)
10-40° Wedge Both Terminators acceptable	$\frac{60}{360}$ = 17%	$\frac{(45 + 30)2}{360}$ = 42% (3)	$\frac{(90 + 30)2}{360}$ = 67% (4)
10-60° Wedge Morning Terminator only	$\frac{50}{360}$ = 14%	$\frac{50 + 45}{360}$ = 26% (2)	$\frac{50 + 90}{360}$ = 39% (3)
10-60° Wedge Both Terminators acceptable	$\frac{100}{360}$ = 28%	$\frac{(50 + 45)2}{360}$ = 53% (2)	$\frac{160 + 90}{360}$ = 70% (3)

The number in parentheses in the multiple site boxes represents the minimum number of acceptable sites for the case considered. The displacement between any two sites can be as great as the wedge angle of the photometric constraint (i.e., 30° or 50°).

Program inflexibility arises from the expectation that launches of this magnitude rarely, if ever, get off the pad on schedule. Therefore, backup time is required to prevent

intolerable delays; and backup time can be obtained with backup landing sites. The cost of certifying extra sites is considerable and must eventually be weighed against the costs in time, effort, and money due to a delayed program which may have depended on a single site. The task here is not to make this judgment, but rather to present the gross landing site constraint picture and indicate the possible tradeoffs.

It is unlikely that any decision on multiple sites could be made until some data on the lunar surface is made available through the unmanned program. These data may drastically change the constraint picture. For instance if the equatorial belt were found to be covered with several large, smooth areas capable of supporting a LEM landing without any aid from the astronaut, the photometric constraint could be relaxed to give single site accessibility for more than 50% of the month.

As a final consideration mention should be made of the one strategy which allows the maximum number of launch windows per month for the minimum unmanned program expenditure, namely, cancel the unmanned program and launch the Apollo spacecraft to an uncertified site. This implies the percentage availability indicated by the third column of the table, appropriate to the selected environmental constraints. The problem is that we dare not risk landing a fragile LEM on what may be an extremely hostile surface.

The advantages in terms of increased LEM hover time and/or a more competent LEM which may be gained by landing at the most economic (from fuel considerations) point within the ±45° band are insufficient to make this a realizable strategy.

CONCLUSIONS

Constraints due to fuel considerations limit the region of acceptable landing sites to an equatorial band between 10° N and 10° S. This band is further limited to 45° E - 45° W through a combination of requirements for navigation, tracking, and communication. Use of Surveyor to certify the sites reduces this further to 0° - 45° W.

Superimposed on top of this is a set of constraints which depends on the rotational period of the moon. This set is composed of the four environmental factors: lunar surface viewing conditions (from LEM), surface temperatures, and astronaut hazard at the surface due to the influxes of solar flare protons and meteoroids. These factors act to limit the number of days during the month when a single landing site within the ±10°, ±45° area may be reached. The result may be as few as 2.3 days per month.

Further, there are constraints with a yearly period which favor some months more than others. A possible earth-based requirement for an in-plane, daylight launch may restrict available launch windows to spring and summer months. Meteoroid flux is low during February and March, with the general summer level a factor of 4 above this. Constraints based on these effects could limit launch windows to a few months of the year which, in combination

with the monthly constraints, could reduce the total number of launch windows to only a handful per year.

Application of all the above constraint possibilities could make the launch program very inflexible. However, several of the individual constraints may be relaxed when relevant data from the unmanned program is available. If at that time the program is still curtailed by an inadequate number of launch opportunities, multiple sites within the ±45° equatorial band will be considered as a method of increasing program flexibility. The tradeoff between the additional effort required to certify an array of sites and the cost of program delay because there is no site available when the launch could be made can only be dealt with when the appropriate weighting factor for each constraint is known. At this time the photometric and thermal constraints appear to be the major time varying factors with the meteoroid and radiation influxes playing a minor role.

Certification of a minimum of one site is required to provide a sufficiently high confidence level for mission safety. Increasing the number of certified sites provides for a larger number of launch opportunities. Assuming the 10° - 40° photometric constraint, two sites spaced 30° apart satisfy the launch requirement for a 3-4 consecutive day period and make optimum use of the 0° - 45° W area for a given number of sites. While two sites provide twice the availability of a single site, a third site is at best half as effective as the second, since the optimum spacing of 30° can no longer be maintained.

Although two or even three sites are desirable for increased launch opportunities, the probability of certifying more than one site with the presently planned unmanned program (see Reference 5) may be quite small. Until the second site is available then, the single site strategy must be entertained.

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